J Arid Land (2023) 15(6): 637–648
https://doi.org/10.1007/s40333-023-0016-5

Science Press Springer-Verlag



# Seasonal variations in glacier velocity in the High Mountain Asia region during 2015–2020

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**Abstract:** Velocity is an important component of glacier dynamics and directly reflects the response of glaciers to climate change. As a result, an accurate determination of seasonal variation in glacier velocity is very important in understanding the annual variation in glacier dynamics. However, few studies of glacier velocity in the High Mountain Asia (HMA) region were done. Along these lines, in this work, based on Sentinel-1 glacier velocity data, the distribution of glacier velocity in the HMA region was plotted and their seasonal variations during 2015–2020 were systematically analysed. The average glacier velocity in the HMA region was 0.053 m/d, and was positively correlated with the glacier area and slope. Glaciers in the Karakoram Mountains had the fastest average flow velocity (0.060 m/d), where the glaciers exhibited the largest average area and average slope. Moreover, glaciers in the Gangdisê Mountains had the slowest velocity (0.022 m/d) and the smallest average glacier area. The glacier flows were the fastest in spring (0.058 m/d), followed by summer (0.050 m/d), autumn (0.041 m/d), and winter (0.040 m/d). In addition, the glacier flows were the maximum in May, being 1.4 times of the annual average velocity. In some areas, such as the Qilian, Altun, Tibetan Interior, Eastern Kunlun, and Western Kunlun mountains, the peak glacier velocities appeared in June and July. The glacier velocity in the HMA region decreased in midsummer and reached the minimum in December when it was 75% of the annual average. These results highlight the role of meltwater in the seasonal variation in glacier flows in late spring and early summer. The seasonal velocity variation of lake-terminating glaciers was similar to that of land-terminating ones, but the former flowed faster. The velocity difference close to the mass balance line between the lake- and land-terminating glaciers was obviously greater in spring than in other seasons. In summer, the difference between the lake- and land-terminating glaciers at a normalized distance of 0.05–0.40 from the terminus was significantly greater than those of other seasons. The velocity difference between the lake- and land-terminating glaciers is closely related to the variable of ice thickness, and also to the frictional force of the terminal base reduced by proglacial lakes. Thus, it can be concluded that in addition to the variation of the glacier thickness and viscosity, the variation of glacier water input also plays a key role in the seasonal variation of glacier velocity.

**Keywords:** glacier velocity; spatial-temporal variations; High Mountain Asia; synthetic aperture radar offset-tracking; climate change

**Citation:** ZHANG Zhen, XU Yangyang, LIU Shiyin, DING Jing, ZHAO Jinbiao. 2023. Seasonal variations in glacier velocity in the High Mountain Asia region during 2015–2020. Journal of Arid Land, 15(6): 637–648. https://doi.org/10.1007/s40333-023-0016-5

## 1 Introduction

Flow is a natural attribute of glaciers and is the main characteristic distinguishing them from other

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Received 2023-01-17; revised 2023-03-30; accepted 2023-04-12

natural ice bodies. Flow is of great significance to the survival and development of glaciers (Cuffey and Paterson, 2010), since it transports the snow and ice mass in the upper accumulation area to the lower ablation area, where it replaces the mass lost due to ablation (Samsonov et al., 2021). When the flow of a glacier is in harmony with its mass balance, the glacier remains stable. If the relationship between the two is out of balance, the glacier advances or retreats (Dehecq et al., 2019). Understanding the temporal and spatial variations in glacier flow under the influence of global warming is of great significance in predicting glacier change (Yan et al., 2021; Yang et al., 2022).

The High Mountain Asia (HMA) region has the most mid-latitude glaciers in the world, and is the largest gathering place of mountain glaciers, which are the sources of many great rivers (Immerzeel et al., 2019; Pritchard, 2019). The HMA region plays a very important role as an ecological security barrier for the sustainable socioeconomic development of Asia (Kraaijenbrink et al., 2016, 2017). In recent years, under the background of climate warming, most glaciers in the HMA region have been in a state of negative mass balance, and their flow characteristics have changed, resulting in a loss of stability that has led to natural disasters such as glacier collapses and glacial lake outbursts (Brun et al., 2017; Dehecq et al., 2019; Nie et al., 2021). Therefore, clarifying the characteristics of glacier flow is an effective way to identify glacier-related environmental changes and disasters in the HMA region.

Due to the limitations of field observation, observed data of glacier flow velocity are very limited, therefore, it is difficult to determine the characteristics of glacier dynamics across the whole HMA region. Synthetic aperture radar differential interferometry (DInSAR), optical satellite images feature tracking techniques, and the synthetic aperture radar (SAR) offset tracking method can extract glacier velocity over large regions and meet the requirements of glaciology (Paul et al., 2015; Sanchez-Gamez and Navarro, 2017; Das and Sharma, 2021; Yang et al., 2022). DInSAR technology is mostly used to obtain glacier velocity in polar continental glaciers. However, mountain glaciers are small in scale and feature complex terrain with severe seasonal melting, which results in severe incoherence of glacier surfaces and difficulty in obtaining glacier velocity by DInSAR (Sanchez-Gamez and Navarro, 2017). Optical remote sensing is greatly disturbed by clouds and snow, making it difficult to obtain seasonal glacier flow characteristics (Paul et al., 2015). In contrast, SAR data from the Sentinel-1 satellite is able to process global glacier velocity by the offset tracking method (Friedl et al., 2021). It has a temporal resolution of up to 6 d, and is unaffected by weather conditions and seasons (Yang et al., 2022).

Remote sensing has played an important role in the study of glacier velocity in the HMA region, including individual glaciers (Wendleder et al., 2018; Yan et al., 2018; Liu et al., 2019), glacierized regions (Sam et al., 2018; Wu et al., 2020; Singh et al., 2021), and the whole HMA region (Dehecq et al., 2019). Dehecq et al. (2019) analysed the inter-annual variations in glacier velocity across the whole HMA region from 2000 to 2017. However, due to data limitations, there is a lack of understanding of seasonal variation characteristics of glacier flow across the HMA region.

Previous studies have proven that glacier velocity has obvious seasonal variation in some regions. The pattern of seasonal variation is heterogeneous, with some glaciers flowing faster in winter (Usman and Furuya, 2018), and some in summer (Sam et al., 2018). For a single glacier, the variation in glacier velocity is more complex, being not only related to changes in glacier thickness but also other factors (Horgan et al., 2015; Schaffer et al., 2017; Sam et al., 2018). Armstrong et al. (2017) attributed seasonal variations in glacier velocity to subglacial drainage change. Burgess et al. (2013) suggested that the accelerated glacier flow in summer was caused by accelerated surface melting. However, Schaffer et al. (2017) found that glacier surface melt rates were not positively correlated with flow velocity. When excessive meltwater enters the ice, it is discharged into a subglacial drainage system rather than staying at the base, resulting in deceleration. In addition, Zhang et al. (2020) suggested that snow cover in winter is also an important driver of glacier velocity. Nonetheless, it is not clear if these theories could be applied to the HMA region, whereas the underlying reasons behind the seasonal variations in the glacier

velocity in the HMA region remain still unclear. Thus, it is apparent that further elaboration is required on these issues.

In order to understand the reasons behind the seasonal variation in glacier velocity, the temporal and spatial characteristics of glacier velocity should be analysed over a large area. Under this perspective, in this work, based on Sentinel-1 glacier velocity data extracted from December 2015 to December 2020, the seasonal variation in glacier velocity in the HMA region was systematically investigated and different flow patterns of the lake- and land-terminating glaciers were examined. Our work not only provides valuable insights for the prediction of future glacier changes by using the glacier dynamics model, but also can be used as a solid basis for the early warning of environmental disasters caused by glacier flow.

## 2 Study area and methods

### 2.1 Study area

The HMA region usually refers to the high-altitude region of Asia centred on the Tibetan Plateau. This region has the densest distribution of mountain glaciers in the world and the third-largest accumulation of glaciers after the North and South Poles, being known as the "Third Pole". The geographical range is 25°–45°N, 65°–105°E, and the altitude is >2000 m a.s.l. (Fig. 1). The HMA region is an important water resource for China, Southeast Asia, and Central Asia. Known as the "Asian Water Tower", it directly affects about $1.6\times10^9$ people (Immerzeel et al., 2019). A total of 95,536 glaciers are located in the MHA region, and cover an area of 107,324 km$^2$ (RGI, 2017). Under the background of westerly-monsoon interaction and global warming, most glaciers are in a state of retreat, which has a significant impact on downstream water resources and aquatic environments (Brun et al., 2017; Zhang et al., 2022a). Therefore, the HMA region has a significant impact on the global water cycle, water resources, and ecological environment in the arid regions of Central Asia.

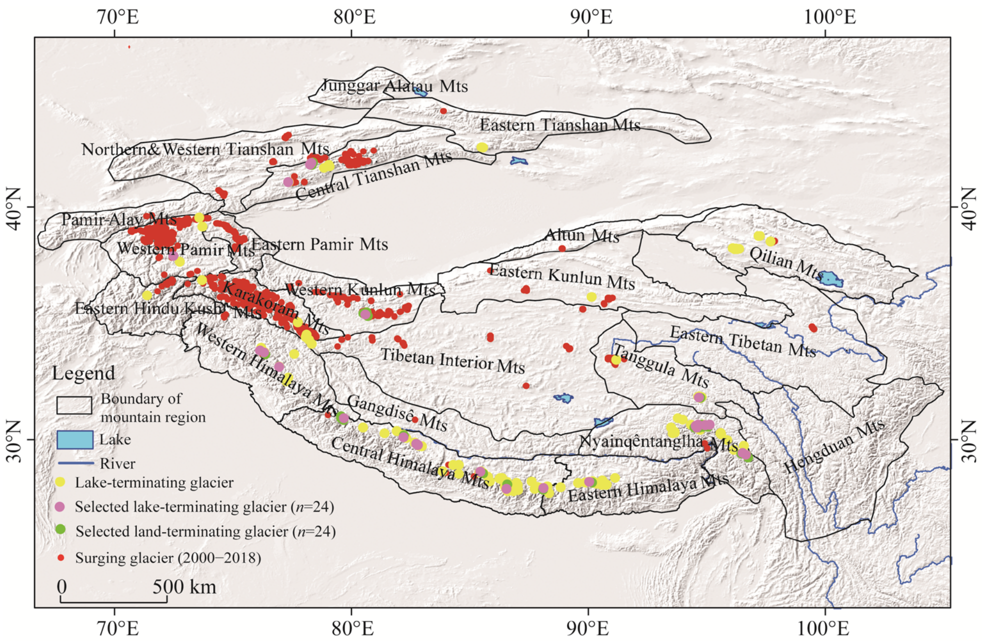


**Fig. 1** Location of the HMA (High Mountain Asia) region and distribution of glaciers. Mountain boundary data are referenced from the following website https://www.mountcryo.org/datasets/. Mts, mountains; *n*, number of samples.

### 2.2 Sentinel-1 and glacier velocity data

The European Space Agency (ESA) launched the Sentinel-1 A and Sentinel-1 B satellites on 3

April 2014 and 25 April 2016, respectively. Each satellite can be revisited every 12 d, while the two satellites can be revisited every 6 d. The satellites carry C-band (5.4 GHz, 5.6 cm) SAR sensors. Based on the offset tracking method, interferometric wide (IW) swath mode images with a range resolution of 5 m and azimuthal resolution of 20 m are used to extract glacier velocity, as described by Friedl et al. (2021). They updated the state vectors of the Sentinel-1 IW single look complex (SLC) images using recalculated precise orbit determination (POD) service precise orbit ephemerides information, which was available within 3 weeks of acquisition, to assure the highest geolocation accuracy (RMSE (root mean square error)=5 cm). Following that, the Sentinel-1 three-step co-registration program was used to accurately register the continuous overlapping image pairs (Wegnüller et al., 2016). Then, Gamma software was used to obtain glacier velocity information by the offset tracking method (Friedl et al., 2021). The offset tracking method uses the moving window to determine the normalized correlation peak between master and slave intensity image patches to obtain the azimuth and tilt distance displacement. The method is based on tracking persistent patterns of intensity values in the two images that are either formed by surface features, such as cracks (feature tracking) or by associated radar speckles (speckle tracking). The latter enables more reliable tracking of radar data over slow-moving accumulations or large ice caps with smooth, featureless surfaces than optical data. In the HMA region, a tracking window size of 250×50 pixels was used, the step size was chosen to be 50×10 pixels in the range, and azimuth directions were utilized. During the tracking process, if the correlation peak coefficient (CCP) is less than 0.08, the invalid displacement measurement will be rejected, while a CCP of 1.00 indicates a complete correlation. However, since this process only removes very bad errors, filtering is also required for later processing steps. Three filtering steps were used: a segmentation filter, a median filter, and a directional filter (Lüttig et al., 2017). Then, common registration errors were corrected, and the displacement and angle were recalculated. Finally, the monthly velocity field was calculated with all the results between the first and the last days of the month, and the final monthly velocity data were obtained after clipping. The accuracy of velocity product is generally consistent with Landsat-8 surface velocity data and TerraSAR-X velocity data. A detailed description of the sentinel velocity data can be found in Friedl et al. (2021), and the data are available at https://doi.org/10.5880/fidgeo.2021.016.

### 2.3 Glacier inventory and velocity along centreline

This study uses the Randolph glacier inventory (RGI) v.6.0 data, which is provided by the global land ice measurements from space (GLIMS). The centreline data were provided by Maussion et al. (2019) on the basis of RGI v.6.0 using open global glacier mode (OGGM). The velocity of each glacier was taken as its velocity along centreline, which was extracted using centreline data and Sentinel-1 velocity data in ArcGIS (geographical information system) software. The data for each season or month were averaged from 2015 to 2020.

### 2.4 Surging glaciers selection

Guillet et al. (2022) judged whether glaciers exhibited surging behaviour based on multi-source data of glacier velocity, elevation, and morphological changes. They finally judged that a total of 666 glaciers exhibited surging behaviour during 2000–2018 in the HMA region (Fig. 1).

### 2.5 Lake-terminating glaciers selection

We screened out data for glaciers intersecting with glacial lakes (Chen et al., 2021) from the glacier inventory data, and then judged whether the glaciers were lake-terminating one by one. A total of 143 lake-terminating glaciers were screened out in the HMA region. To study the seasonal pattern of surface velocity of lake- and land-terminating glaciers, we selected 24 lake-terminating and 24 land-terminating glaciers with areas >10 km$^2$. The total area, slope, and geographical location of these two types of glaciers were similar (Fig. 1).

### 2.6 Glacier velocity uncertainty evaluation

Due to the difficulty of field measurement, this study used an indirect method to evaluate the

uncertainty in glacier velocity. Glacier velocity is generally significantly faster than tectonic movement on the surface of ice-free stable terrain. Therefore, we assumed that there was no displacement change in the ice-free stable terrain; that is, the true value of velocity in the ice-free stable terrain was 0. We also assumed that the glacier regional error was consistent with that of ice-free stable terrain, so the ice-free stable terrain error was used as the glacier velocity error (Zhang et al., 2022b). The velocity error ($E_{\text{off}}$) in the ice-free stable terrain region was evaluated by Equations 1–3.

$$E_{\text{off}}=\sqrt{{E_m}^2+{E_s}^2}\,, \tag{1}$$

$$E_s=\frac{\sigma}{\sqrt{N_e}}\,, \tag{2}$$

$$N_e=\frac{N_t\times R}{2D}\,, \tag{3}$$

where $E_m$ is the average velocity of ice-free stable terrain (m/d); $E_s$ and $\sigma$ are the standard error (m/d) and standard deviation (m/d), respectively; $N_e$ is the number of effective pixels removing the effect of spatial autocorrelation; $N_t$ is the number of pixels of ice-free stable terrain; $R$ is the pixel resolution; and $D$ is the spatial autocorrelation distance (generally 20 times the pixel resolution (Sun et al., 2017)).

## 3 Results

### 3.1 Spatial characteristics of glacier velocity

From 2015 to 2020, the average glacier velocity in the HMA region was 0.053 m/d and the uncertainty was 0.013 m/d (Fig. 2; Table 1). The glacier velocity in the Karakorum Mountains was the fastest (0.077 m/d). Even excluding the statistics of surging glaciers, the Karakorum Mountains had the fastest glacier velocity (0.060 m/d), because these glaciers had the largest average area and average slope. The glacier velocity of the Eastern Hindu Kush Mountains was the second fastest in the HMA region, with the glacier velocities of the Altun, Central/Western Himalaya, Nyainqêntanglha, and Pamir-Alay mountains being >0.05 m/d. The average slope of the Altun Mountains glaciers was the highest, while the average area of the Central/Western Himalayan glaciers was the largest. However, the average area and slope of glaciers in the Eastern Hindu Kush, Pamir-Alay, and Nyainqêntanglha mountains were less than the average for the HMA region. These mountainous regions may be influenced by different local climates and glacial properties. The Eastern Hindu Kush and Pamir-Alay mountains are influenced by westerly winds. The Nyainqêntanglha Mountains is influenced by the south Asian monsoon, and has temperate or marine glaciers. The Gangdisê Mountains had the slowest glacier flow (0.022 m/d) and the smallest average glacier area. The glacier velocities in the Qilian, Tanggula, Eastern Tianshan, and Junggar Alatau mountains were also <0.040 m/d, and the average glacier areas of these mountains were smaller in the HMA region.

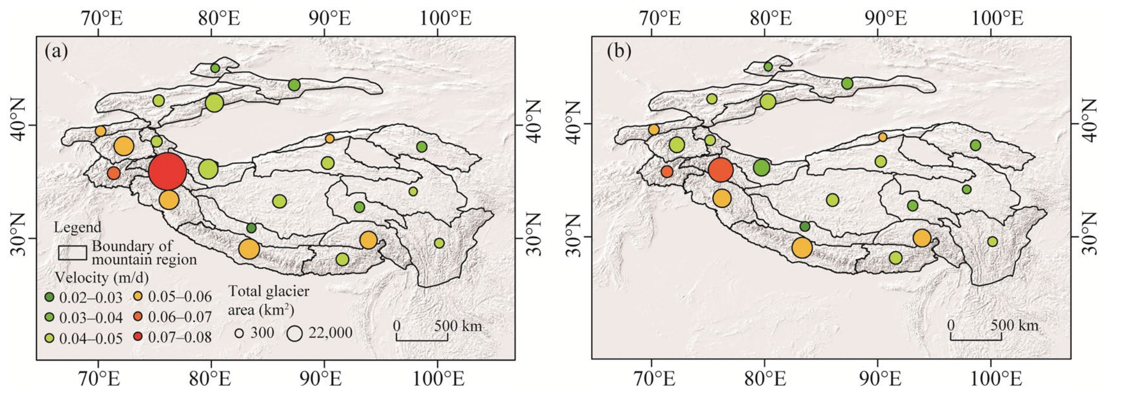


**Fig. 2** Glacier velocities in different mountains for all glaciers (a) and excluding surging glaciers (b)

**Table 1** Average glacier area, slope, and velocity of the mountains

| Mountains | Average area ($km^2$) | | Average velocity (m/d) | | Uncertainty (m/d) | Average slope (°) | |
|---|---|---|---|---|---|---|---|
| | IS | NS | IS | NS | | IS | NS |
| Altun Mts | 0.63 | 0.60 | 0.055 | 0.054 | 0.009 | 27.235 | 27.269 |
| Central Himalaya Mts | 1.18 | 1.18 | 0.051 | 0.051 | 0.010 | 26.353 | 26.352 |
| Central Tianshan Mts | 1.25 | 0.98 | 0.048 | 0.045 | 0.015 | 26.615 | 26.676 |
| Junggar Alatau Mts | 0.54 | 0.54 | 0.037 | 0.037 | 0.017 | 23.698 | 23.698 |
| Eastern Himalaya Mts | 1.07 | 1.06 | 0.049 | 0.049 | 0.012 | 23.569 | 23.567 |
| Eastern Hindu Kush Mts | 0.67 | 0.63 | 0.062 | 0.060 | 0.009 | 24.739 | 24.752 |
| Eastern Kunlun Mts | 0.97 | 0.81 | 0.046 | 0.044 | 0.007 | 24.162 | 24.201 |
| Eastern Pamir Mts | 1.34 | 0.90 | 0.049 | 0.041 | 0.011 | 26.929 | 26.961 |
| Eastern Tibetan Mts | 0.60 | 0.53 | 0.041 | 0.039 | 0.012 | 23.628 | 23.650 |
| Eastern Tianshan Mts | 0.55 | 0.55 | 0.035 | 0.035 | 0.014 | 27.606 | 27.605 |
| Gangdisê Mts | 0.33 | 0.33 | 0.022 | 0.022 | 0.005 | 23.986 | 23.990 |
| Hengduan Mts | 0.62 | 0.62 | 0.043 | 0.043 | 0.013 | 23.059 | 23.059 |
| Karakoram Mts | 1.85 | 1.04 | 0.077 | 0.060 | 0.012 | 31.277 | 31.398 |
| Northern&Western Tianshan Mts | 0.58 | 0.54 | 0.042 | 0.041 | 0.016 | 23.117 | 23.151 |
| Nyainqêntanglha Mts | 0.95 | 0.95 | 0.058 | 0.058 | 0.013 | 24.913 | 24.912 |
| Pamir-Alay Mts | 0.59 | 0.58 | 0.053 | 0.052 | 0.012 | 25.219 | 25.225 |
| Qilian Mts | 0.60 | 0.57 | 0.032 | 0.031 | 0.008 | 26.423 | 26.45 |
| Tanggula Mts | 1.16 | 0.97 | 0.035 | 0.034 | 0.013 | 21.361 | 21.446 |
| Tibetan Interior Mts | 1.09 | 0.99 | 0.049 | 0.045 | 0.006 | 22.568 | 22.623 |
| Western Himalaya Mts | 0.81 | 0.79 | 0.057 | 0.056 | 0.011 | 24.307 | 24.309 |
| Western Kunlun Mts | 1.49 | 1.13 | 0.042 | 0.039 | 0.007 | 26.450 | 26.548 |
| Western Pamir Mts | 0.93 | 0.62 | 0.057 | 0.047 | 0.011 | 26.649 | 26.756 |
| HMA | 1.02 | 0.83 | 0.053 | 0.049 | 0.013 | 25.926 | 25.956 |

Note: IS, including the surging glacier; NS, surging glaciers were not included in the statistics; HMA, High Mountain Asia; Mts, mountains.



### 3.2 Seasonal variation in glacier velocity

To study the seasonal variation of glaciers, we calculated the monthly enhancement factor, which is defined as the ratio of monthly average velocity to annual average velocity. Enhancement factors>1.0 indicate that the velocity in that month was greater than the annual average; while factors<1.0 indicate a lesser velocity, and factors=1.0 indicate an equal velocity. The variations in monthly glacier velocity were similar regardless of whether surging glaciers were included. The enhancement factors from March to July were >1.0, that is, the average glacier velocity in these months were higher than the annual average. The enhancement factor in May was the highest; i.e., which was 1.4 times of the annual average (Fig. 3). December had the lowest enhancement factor (75% of the annual average).

If we define spring as March to May, summer as June to August, autumn as September to November, and winter as December to February, then the spring glacier velocity was the fastest (0.058 m/d), followed by summer (0.050 m/d; Fig. 4). Glacier velocities were the slowest in autumn and winter (0.041 and 0.040 m/d, respectively). Combined with the above results, the average glacier velocity was the highest in late spring and early summer (May–June). The glacier velocity of most mountain regions (Figs. 5 and 6) was the highest in May, but those of the Qilian, Altun, Tibetan Interior, Eastern Kunlun, and Western Kunlun mountains were the highest in June and July, which may be related to their glacier accumulation mainly occurring in summer. Although the peak glacier velocities in these regions lagged those of other regions, they also decreased after July and August.

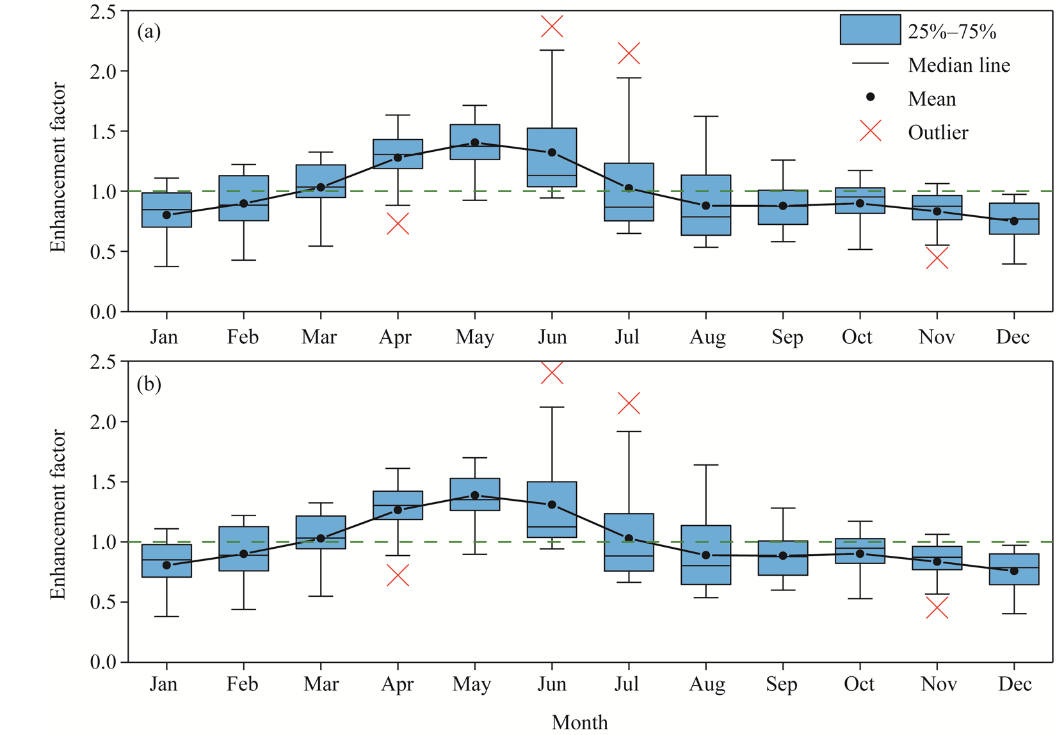


**Fig. 3** Monthly velocity enhancement factors for all glaciers (a) and excluding surging glaciers (b). The horizontal dashed line in green is a horizontal line at $y$=1.0, representing the monthly average glacial velocity is equal to the annual average glacial velocity.

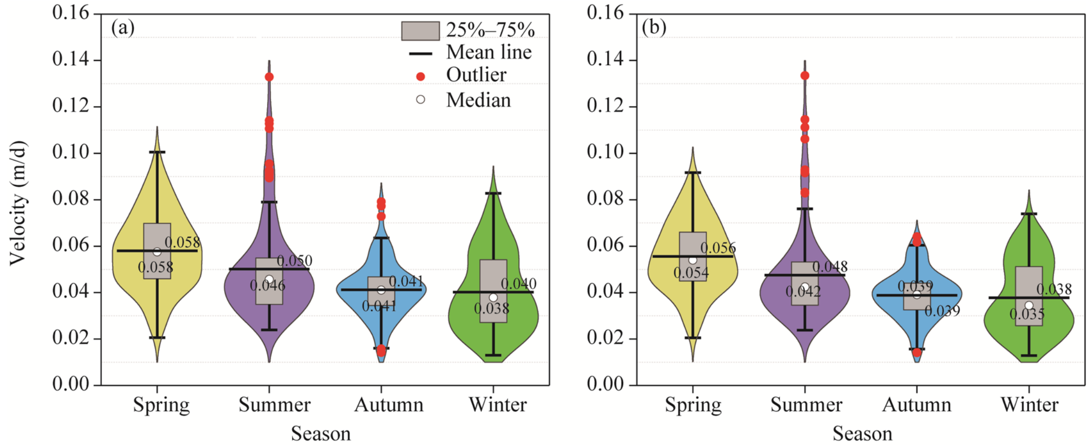


**Fig. 4** Seasonal velocities of all glaciers (a) and excluding surging glaciers (b). The upper and lower black bars represent a range defined as all values 1.5 times the interquartile range larger (smaller) than the third (first) quartile.

### 3.3 Comparison of velocities of lake- and land-terminating glaciers

For both lake- and land-terminating glaciers, the maximum velocity along centreline occurs near the median altitude, which is usually close to the altitude of mass balance line. The ice in there tends to be the thickest and is the maximum volume. The velocity of a lake-terminating glacier is greater than that of a land-terminating glacier flow in all seasons (Fig. 7). The difference in the glacier velocity near the mass balance line between lake- and land-terminating glaciers is obviously greater in spring than in other seasons. In summer, at a normalized distance of 0.05–0.40 from the terminus, the velocity of land-terminating glaciers slows down, while that of

lake-terminating glaciers accelerates significantly. The difference between the two types of glaciers is significantly greater in summer than those of other seasons.

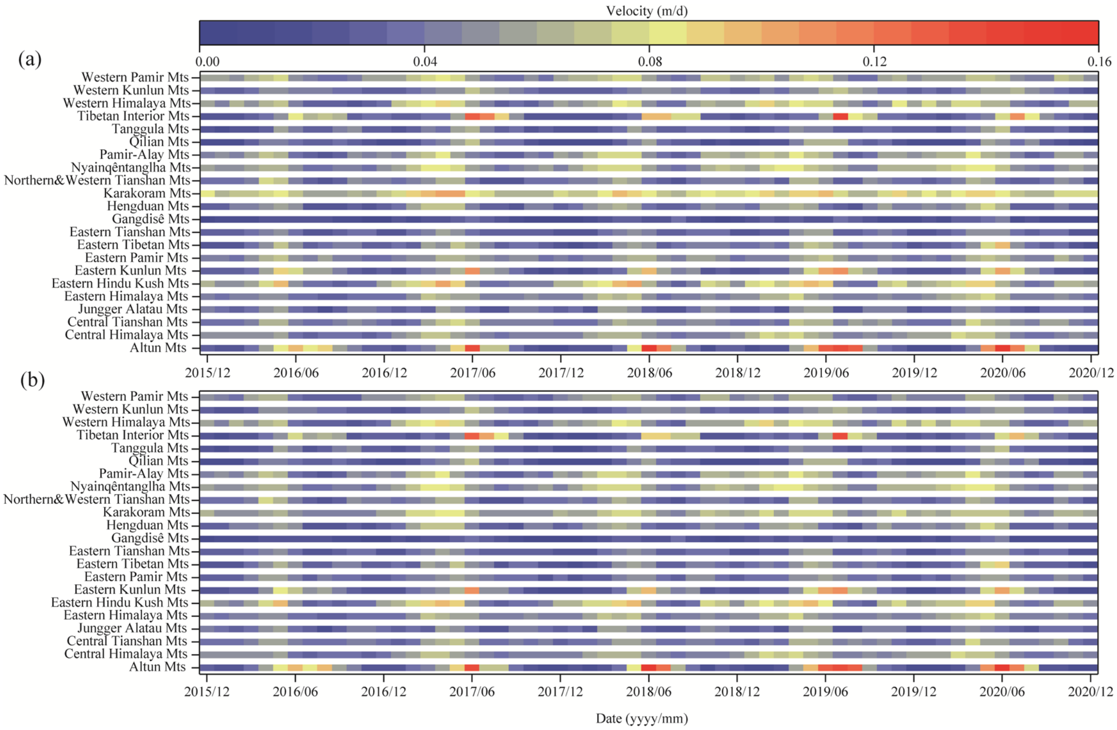


**Fig. 5** Regional interannual variations in the velocities of all glaciers (a) and excluding surging glaciers (b)

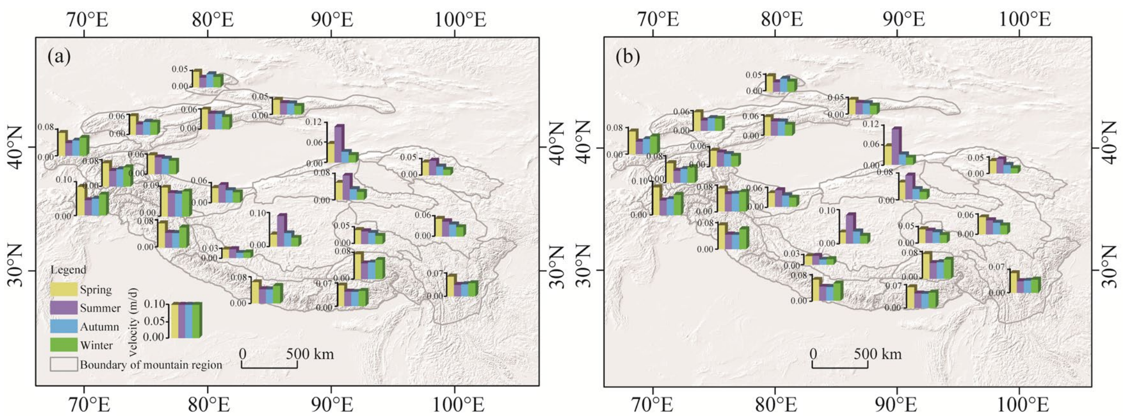


**Fig. 6** Regional seasonal velocities of all glaciers (a) and excluding surging glaciers (b)

## 4 Discussion

### 4.1 Seasonal variation of glacier velocity in the MHA region

In warm season, the temperature of glacier is relatively high, the viscosity of ice decreases rapidly, its plasticity increases, and the glacier velocity accelerates. As a result, seasonal variations of glacier flow are induced (Cuffey and Paterson, 2010). In this work, it was also demonstrated that glaciers flow was faster in warm seasons. Nonetheless, the peak of their flow tends not to occur when temperature values are the highest, but takes place in late spring and early summer. Regionally, the peak velocity occurs in May in most areas, and in June or July in the inner areas of the Tibetan Plateau (the Qilian, Altun, Tibetan Interior, Eastern Kunlun, and Western Kunlun

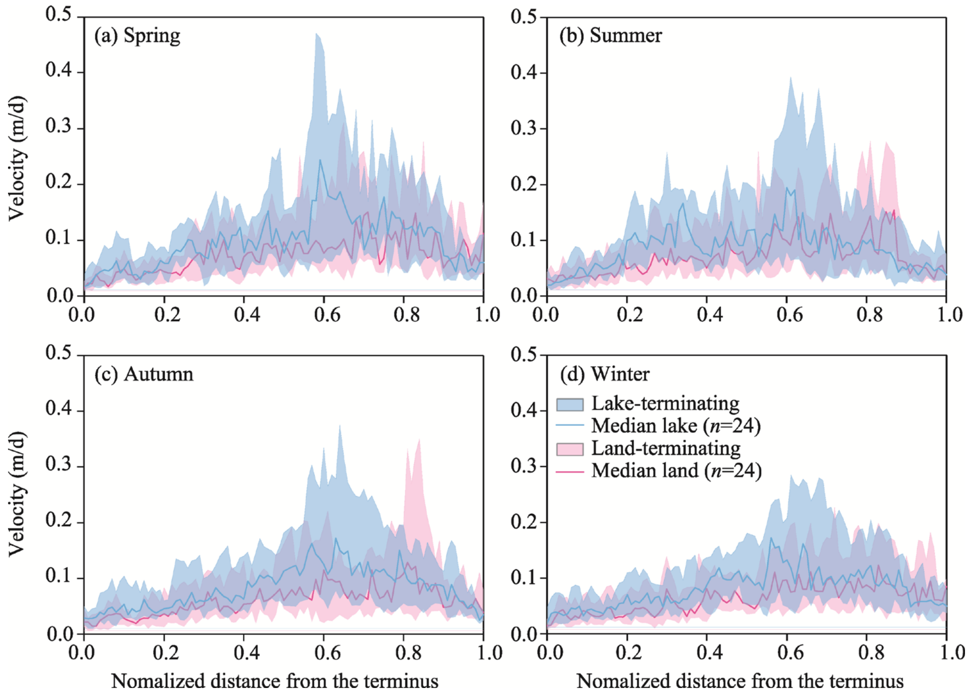


**Fig. 7** Glacier velocity profiles along centreline for different types of glaciers in different seasons. The median and interquartile ranges are shown in bins of size 0.01. Each glacier's centreline length is used to normalize the distance from its terminus. (a), spring; (b), summer; (c), autumn; (d), winter.

mountains). The glacier velocity gradually decreases after late spring and early summer. This seasonal variation is consistent with observations of glaciers in many other regions, such as Alaska (Yang et al., 2022), Greenland (Howat et al., 2010), and Svalbard Archipelago (Schellenberger et al., 2015). These seasonal variations of glacier velocity are related to basal motion caused by meltwater and to changes in the efficiency of drainage systems. When the spring ablation season begins, ice and snow meltwater enter inefficient drainage beds, resulting in increased water pressure and reduced basal resistance, which leads to accelerated glacier flow. An efficient glacial drainage system is then formed in summer. Therefore, the glacier velocity gradually slows until the meltwater input is reduced, and the system reverts to a distributed system. In the inner areas of the Tibetan Plateau, snowfall mainly occurs in summer (Shen et al., 2022), as does the melting of snow, so the glacier velocities in these areas are the highest in summer.

Most mountain areas have a secondary peak in glacier velocity in winter, especially in the Karakoram and Eastern Hindu Kush mountains in December (Fig. 5). This may be related to the dynamic thickening of glaciers within this year. Winter precipitation and glacier accumulation lead to a slight increase in glacier thickness and glacier creep rate, and a slight acceleration in surface flow (Zhang et al., 2020). Snowfall in the areas affected by westerlies is significant in winter (Yao et al., 2012), which makes the glaciers in the Karakoram and Hindu Kush mountains flow faster at that time. Glacier velocity in winter is the lowest in the inner areas of the Tibetan Plateau, where there is little winter precipitation and the climate is cold.

### 4.2 Comparison of seasonal variation of glacier velocity with other studies

There are no studies of seasonal changes in glacial velocity across the entire HMA region; thus, we make comparisons with the studies of seasonal changes in glacier velocity in certain regions or groups of glaciers. Zhang et al. (2020) studied the seasonal variation in the velocity of four glaciers in the Nyainqêntanglha Mountains from March to October (summer) and from October to March (winter). Their results showed that the velocity was greater in summer in the downstream

part of the glacier, but it was greater in winter in the upstream part. It was also demonstrated (Fig. 7) that the upstream flow velocity in summer was lower than that in winter, while the downstream flow velocity was higher than that in winter, which is consistent with the results of Zhang et al. (2020). The upstream ice and snow thinning, lower overburden pressure, slow glacier flow, downstream ice, and snow meltwater participation leads to faster glacier flow in summer. Wu et al. (2020) also found that glaciers in the Nyainqêntanglha Mountains flow faster in summer (May–October), which is consistent with our finding that glaciers flow faster in May. Yang et al. (2020) found that Parlung No. 4 Glacier in the Nyainqêntanglha Mountains flowed faster in the colder season (September–June) than in the warmer season (June–September). Fu et al. (2021) also made a similar conclusion, i.e., Dagongba Glacier in the Hengduan Mountains flowed the fastest from May to October. Sam et al. (2018) observed that the glacier velocity of the Himalaya Mountains was higher in April–August than in other seasons. However, none of these works divided summer into early summer and late summer. Here, the changes in the monthly resolution were studied and it was found that early summer (or late spring) had higher glacier velocity than late summer and also higher than winter. Interestingly, these outcomes are consistent with the above-mentioned studies. The meltwater input at the beginning of early summer (or late spring) will be accelerated by increasing water pressure and decreasing basal drag. With the development of efficient channelized subglacial drainage systems capable of holding large amounts of meltwater, glaciers gradually slowed down until the system reverted to a distributed system with reduced meltwater input (Yang et al., 2022).

### 4.3 Comparison of velocities between lake- and land-terminating glaciers

Our study found that flow velocity of ablation area of lake-terminating glaciers was higher than that of land-terminating glaciers. The variable of ice thickness should be considered here. Lake-terminating glaciers are thicker because they end abruptly at a calving cliff rather than having a gradually thinning leading edge. Since ice thickness drives ice flow, a large part of flow velocity difference between lake- and land-terminating glaciers can be attributed to differences in this factor (Pronk et al., 2021). Proglacial lakes reduce the frictional force of terminal base, which is another reason for the rapid flow of lake-terminating glaciers. We also found that velocity of lake-terminating glaciers was not necessarily faster than that of land-terminating glaciers when normalized distance from the terminal was 0.00–0.05, which may be related to the proglacial lakes melting.

### 4.4 Limitation and recommendation

In this work, the common patterns of glacier flow in the HMA region were explored. In fact, some glaciers may have anomalous behaviours, such as instability of the glacier flow. The latter may have a series of continuous bands, such as hourly, daily, monthly, seasonal, annual, and decadal variations (Herreid and Truffer, 2016). Glacier surging is only an external manifestation of the instability of the glacier flow, and the underlying mechanism is still unclear. On top of that, the law of other types of glacier flow instability is even less well understood. The underlying reason is that there are few experimental observations of glaciers with high precision and high spatial and temporal resolution. Although our work can assess the variation trend of the monthly scale, it is difficult to carry out large-scale observation on the daily scale and hourly scale. In addition, the employed time series length was short, and some glaciers, such as the Trapridge Glacier in the Yukon Territory, Canada, experience 20 a fluctuations in the velocity of glacier flow known as the "slow surge" (Frappé and Clarke, 2007), whose erratic flow patterns are harder to be monitored. Therefore, it is suggested that future monitoring of glacier velocity should focus on the direction of high spatial and temporal resolution, with high precision and utilization of longer time series.

This study did not consider many of factors known to influence glacier flow, such as debris cover, accumulation, ablation areas, supraglacial lakes, ice cliffs, spatio-temporal variation in the velocity of surging glaciers, and glaciers at risk of ice collapse. For this, long time series of more targeted and accurate data need to be combined with dynamic models for the detailed analysis of geometric parameters, such as glacier length, area, and surface elevation, to better understand the

influence of glacier velocity dynamics.

## 5 Conclusions

In this study, the spatial distribution and seasonal variation of glacier velocity in the HMA region were analysed by using Sentinel-1 glacier velocity data. We found that average glacier velocity in the HMA region was 0.053 m/d. Glacier flows were the maximum in May and the minimum in December. However, the peak velocity appeared in June and July in the Qilian, Altun, Tibetan Interior, Eastern Kunlun, and Western Kunlun mountains. There are some similarities between seasonal velocity variations of land- and lake-terminating glaciers, but the latter flow more rapidly. There may also be seasonal variations in surface velocity due to retention of meltwater within glaciers. We suggest further analysing the influences of ice deformation, water, and other factors on glacier flows in combination with dynamic modelling.

## Acknowledgements

This research was supported by the Major Project on Natural Science Foundation of Universities in Anhui Province (2022AH040111) and the National Natural Science Foundation of China (42071085, 41701087).



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